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STUDY OF OPTICAL TECHNIQUES FOR THE AMES UNITARY WIND TUNNELS PART 3. ANGLE OF ATTACK

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CONTENTS.....1

Summary.....	2
Introduction.....	2
Purpose.....	3
The Angle of Attack Mechanism.....	3
Non-optical Sensors.....	4
Optical Techniques.....	5
Laser Angle Meter.....	5
HP Interferometers.....	6
Polarized Light Sensor.....	6
Electro-Optical Photodiodes.....	7
Lateral-Effect Position Sensor.....	9
Saab Elopotos.....	10
RAE Yaw Meter.....	11
Selspot Camera Systems.....	12
Boeing BART.....	13
Line Scanner.....	14
Holographic Optical Elements.....	14
Recommendations.....	15
References.....	16-18
Figure 1. Boeing Laser Angle Meter. (after Pond and Hill).....	19
Figure 2. Angle Measurement Scheme Using Hewlett-Packard.....	20
Interferometers.	
Figure 3. Polarized Light Angle Sensor. (after Crites).....	21
Figure 4. Linear Photodiode Array Displacement Measurement.....	22
(after Schott and Tchong)	
Figure 5. Compleare Lateral-Effect Angle Sensor.....	23
(after McDevitt and Owen).	
(a). Beam Displacement Due to Refraction.....	23
(b) Sketch of Sensor in Wind Tunnel.....	23
Figure 6. SAAB Eloptopos Angle Sensor. (after Fuijkschot).....	24
Figure 7. RAE Yaw Angle Meter. (after Jeffery, Tuck and Law).....	25
Figure 8. Selspot Angle Measurement Scheme. (after George.....	25
and Wolski)	
Figure 9. Holographic Optical Element Measurement Scheme.....	26

Study of Optical Techniques for the Ames Unitary Wind Tunnels.

Part 3. Angle of Attack

Summary

A review of optical sensors that are capable of accurate angle of attack measurements in wind tunnels have been conducted. These include sensors being used or being developed at NASA Ames and Langley Research Centers, Boeing Airplane Company, McDonald Aircraft Company, Arnold Engineering Development Center, National Aerospace Laboratory of the Netherlands, National Research Council of Canada, and the Royal Aircraft Establishment of England. Some commercial sensors that may be applicable to accurate angle measurements were also reviewed. It was found that the optical sensor systems were based on interferometers, polarized light detector, linear or area photodiode cameras, position sensing photodetectors, and laser scanners. Several of the optical sensors can meet the requirements of the Ames Unitary Plan Wind Tunnel. Two of these, the Boeing interferometer, and the Complexe lateral effect photodiode sensors are being developed for the Ames Unitary Plan Wind Tunnel.

Introduction

During the past 10 to 15 years, there has been a large effort to design fuel efficient airplanes. Much work was done to design low drag transports cruising at transonic speeds. This led to the requirement to measure the drag of wind tunnel models very accurately. Many aerodynamicists feel that an accuracy of one drag count in the drag coefficient is necessary. Since wind tunnels use force balances to measure drag and the drag is derived by coordinate transformation that is dependent on the angle of attack, an accuracy of one drag count translates to an accuracy of 0.01 degree angle of attack. Both NASA and industry have been developing angle of attack sensors to meet this accuracy requirement. NASA Langley Research Center has focused their efforts on improving the accuracy and reliability of servo accelerometers. Development work was also done in the area of interferometry and linear photodiodes.

Boeing Airplane Company developed a laser interferometric sensor and is working on a laser range tracking sensor. McDonnell Aircraft Company developed a sensor based on the detection of the intensity of angular modulated polarized light. NASA Ames Research Center has been looking at better capacitive inclinometers and electrolytic potentiometers. They are also sponsoring the development of a lateral effect photodetector. Ames has also been conducting joint programs with Langley, Boeing, and McDonald to evaluate their systems in the Ames Unitary Plan Wind Tunnel. These joint programs have shown the accuracies attainable, the promise of improvement and the limitations. Current plan is to obtain and test the Boeing laser angle meter next year. The lateral effect sensor being developed for Ames by Complere, Inc. will be tested this year. During the past decade, development work in robotic vision, laser scanners, and automated inspection have come up with angular and position sensors. This work should also be useful for the angle of attack problem.

Purpose

The purpose of this study is to critically review the optical techniques being used or being developed for angular measurements. Emphasis will be placed on those instruments that are suitable for the NASA Ames Unitary Plan Wind Tunnel and those that are proven or commercially available.

The Angle of Attack Mechanism

The typical Ames Unitary Plan Wind Tunnel angle of attack mechanism consists of a sting on a strut that spans the test section. The mechanism located in the strut has gears and bearings and motor to pitch, yaw and roll the model. As the model is pitched, it is also translated downstream so that the model stays near the centerline of the test section. For inertial sensors mounted within the model, the combined rotational and translational motions are irrelevant to the angle of attack measurement. However, for optical angle of attack sensors, the additional translational movements make the measurement more complicated. This usually means that the model has to be tracked and may require a tracking system for some of the optical techniques. Note that the 11x11 Foot Transonic and the 8x7 Foot Supersonic Wind Tunnels pitch the model in the vertical

plane. The 9x7 Foot Supersonic Wind Tunnel pitches the model in the horizontal plane. This could affect the deployment of the angle of attack sensing systems. The 11x11 Foot Transonic Wind Tunnel also has a floor mounted model system that rotates the model to attain the angle of attack. This again may require modifications to the sensor system.

Non-optical Sensors

Many of the wind tunnels are currently using non-optical sensors for angle of attack measurement. One class of sensors are inertial sensors¹⁻³ that derive the angle of attack with respect to gravity. Servo accelerometers have been designed on the principles of (1) oil-damped strain gaged cantilever flexure; (2) air-damped translational suspension flexure; (3) oil-damped pendulous metallic flexure and (4) air damped pendulous fused quartz flexure. Another class of inertial sensor⁴ is a design based on the change in electrical capacitance due to gravity. The inertial devices have slow response because of the damping. They also suffer the "sting whip" error caused by centrifugal accelerations from model vibrations. The "sting whip" error inherent in inertial sensors is difficult to correct. According to Finley³, inertial sensors can achieve 0.01 degree accuracy under the ideal conditions of smooth wind tunnel operating conditions, proper installation of the sensor package, and adequate data acquisition and reduction. Inertial devices cannot measure angles in the horizontal pitch plane. This precludes their use in the Ames 9x7 Supersonic Wind Tunnel where the pitch plane is horizontal. The third class of inertial sensors are liquid bubbles. Electrolytic bubble sensors that act like a liquid potentiometer are quite accurate. However, Wong⁵ has shown that they are too slow and become inaccurate in a wind tunnel environment. Angle of attack is also measured by electro-mechanical encoders. The accuracy of this method is poor due to the gears, bearings and the other mechanical moving parts. Based on the 9x7 Supersonic Wind Tunnel system, it is probably not possible to approach 0.01 degree accuracy with electro-mechanical encoders.

Optical Techniques

Laser Angle Meter

The Boeing laser angle meter is a system using interferometric techniques to measure angle of attack to accuracies of 0.005 degrees. Typical range is 4 to 5 meters. Development of this sensor was started in the 1970's and it has been tested in the Boeing Transonic Wind Tunnels and in the NASA Ames and Langley wind tunnels. The system consists of an optical transmitter mounted outside the test section and a reflector assembly mounted in the model. The transmitter contains a laser, servos and photodetectors, and electronic processor. The reflector assembly contains a hologram and a retro-reflector. Basically, the system acts like a shearing interferometer and a change in angle of attack is obtained by counting the phase shift of fringes created by the shearing interferometer. The scheme, figure 1, works as follows: As the laser beam hits the hologram, a first order diffracted beam is created. Another first order diffracted beam is created from the reflected beam from the retro reflector. The two first order beams are collected at the transmitter and the phase shifts between them are detected and counted. The transmitter also functions as a tracker unit. Within the transmitter is an identical retro reflector arc servo unit to rotate the transmitter so that the laser beam can follow the reflector assembly in the model. The system was designed so that the angular changes in the transmitter is automatically accounted for in calculating the angle of attack. A detailed description of this sensor, the operational and calibration procedures, electronics and design are given by Pond, Hill, Crowder, and Texeria⁶⁻¹⁰.

The positive aspects of this system are that (1) it has been demonstrated that it can operate in large wind tunnels; (2) it easily meets the required accuracy; (3) it operates in real-time with no lag; and (4) any roll from the sting mechanism does not affect the angle of attack measurement.

The limitations are any opaque obstruction, such as a cloud of fog in the airstream, will cause the system to lose the angle position. The system will have to be at re-set at the reference zero condition which may require a shutdown of the wind tunnel. This would be costly and time consuming. A

second limitation is that a contoured window matching the model geometry needs to be made to cover the reflector assembly and not disturb the flow over the model. If this window shape is complex, i.e. not flat or cylindrical, it would be expensive to make. Finally, the large translational motions of the Ames angle of attack mechanism will require a translation platform to move the transmitter so that the beam can track the model. This could be a source of error.

HP Interferometers

Hewlett Packard⁶ has a complete commercial line of laser interferometers that can measure distances to sub-micron accuracies. These units are Michelson interferometers that have been demonstrated to operate in many machine shop environments. The units consist of a stable laser with two output beam transmitter, retro reflector, and electronics to count the fringes. The system is small enough to mount the retro reflectors in the model and the transmitters outside the test section. The scheme to measure angle of attack, figure 2 would have two HP interferometers sending parallel beams to the model. The distances d_1 and d_2 are measured and the angle of attack is calculated. The HP based system has the same opaque obstruction, contoured window limitations as the Boeing laser angle meter.

Polarized Light Sensor

An angle of attack sensor has been developed by Crites¹² using angular modulation of plane polarized light. This sensor is being used in the McDonnell Aircraft Polysonic Blow-down Wind Tunnel. The principle of angular modulation of plane polarized light is based on the fact that transmission of plane polarized light by a linear polarizer is a function of the angle between the polarization axis of the incident light and the polarization axis of the polarizer. When the axes are parallel, maximum light is transmitted. When the axes are normal, minimum light is transmitted. A sketch of the system is shown in figure 3. A 30 watt lamp with a polarizer plate mounted outside the test section creates a plane polarized beam that illuminates the model. A receiver assembly mounted in the model consists of a polarizer and a photodiode detector. Two receivers with the polarizers at 90 degrees are required because the photodiodes cannot distinguish the change in intensity from the angle of attack changes and any

lamp intensity change. With two receivers, the effects of any lamp intensity change can be measured. This system was tested in the Ames 11x11 Foot Transonic Wind Tunnel in 1990. Significant errors were introduced by the wind tunnel fluorescent lights used to monitor the model. In the McDonnell wind tunnel, all other lights are turned off. However, with suitable filters for the different wavelength lamps, the problem could be resolved. The advantages of this sensor are: (1) does not use a laser, with its safety problems; (2) simple design and low cost, about a few thousand dollars. The limitation is that its accuracy is only about 0.03 degree. However, part of the poor accuracy can be attributed to be backlash and loose sting drive mechanism of the Polysonic Wind Tunnel. Another contribution to the poor accuracy is the model rolls a little as it is pitched. Recent discussions with R. Crites indicated that laboratory calibrations gave resolutions of 0.003 degree. Therefore, there is a good possibility that this sensor can achieve the required goal of 0.01 degree.

Electro-Optical Photodiodes

NASA Langley Research Center has been developing a high resolution systems¹³⁻¹⁵ for detecting the position and angle of attack of models in the 13-Inch Magnetic Suspension and Balance System Facility. This position detection system is based on measuring the shadows cast by the model from collimated laser beams. During the initial development of this program, two schemes were tried. First, a linear photodiode array camera was used to measure the edges of the shadow. The second scheme used an area array camera to measure targets attached on the model surface. Fourteen cameras mounted outside the test section was used to locate the targets from various angles. At the time of this program, the linear photodiode arrays had about 4000 pixels over a length of 4 inches. the area arrays had about a few hundred by few hundred pixels. This limitation of size and pixels required the acquired images to be processed to sub-pixel accuracies. For both linear and area arrays, the approach was to locate the object with rough tracking algorithms and then with a fine tracking algorithm to obtain the sub-pixel resolutions. For the linear array, a simple thresholding was used as the rough tracking algorithm to locate the edges. For the area array, a matched spatial filter was used for the rough search. For the fine tracking schemes to get the sub-pixel resolutions, a moment matching algorithm and a five point centroid algorithm was used for the

linear and area arrays, respectively. The study of La Fleur¹³ indicated that both linear photodiode and area photodiode cameras could satisfy the range and accuracy requirements of the Magnetic Suspension Facility. However, the linear photodiode camera was chosen as the sensor system. It is suspected that area array camera approach was not chosen because of the large number of cameras required.

Two electro-optical positioning systems using linear photodiodes were constructed. The first system¹⁵ was a five component system to measure pitch, yaw, and the vertical, horizontal and axial locations of the model. The system used linear photo diodes having 1024 elements, a resolution of 0.001 inch and a 1 inch long aperture. 2 mw HeNe lasers were used to provide the light beams. Laboratory calibrations shown that overall precisions of 0.02 degree were obtained. To improve the range and precision, a second system¹⁴ using a 4096 element photodiode with an aperture of about 2.4 inches was built. The angular precision was improved to 0.015 degree. The typical arrangement of the system is shown in figure 4. It consists of the laser and associated optics, two linear photodiode arrays and interface electronics, a two channel shadow edge-detection electronics package, and a line driver-receiver system. A low power HeNe laser with cylindrical glass rods is used to create two vertical uniform sheets of light that is projected across the test section. The model is positioned so that it blocks both sheets of light and the shadows from the model are measured by the linear photodiodes located on the other side of the test section. Details of the system are given in a paper by Schott and Tcheng.¹⁵

The advantages of this system are that it is passive. There are no moving parts and no sensors are required to be put on the model. It can measure real-time angle of attack over a large angle of attack range. It can operate and keep track of the angle (i.e. no signal drop-out) when the beams are temporarily obstructed by tunnel fog. The limitations are the model geometry must be simple. (Perhaps, the angle of the sting could be measured and the model angle can be derived.) The apertures of currently available photodiodes are limited to a few inches which would preclude this type of scheme from a large wind tunnel like the Ames Unitary Plan. There are commercial photodiodes that can be quite large, at least a couple of feet or even more. The photodiodes are

based on a new semiconductive material, hydrogenous amorphous silicon instead of crystalline silicon.

Lateral-Effect Position Sensor

Another class of photodiodes called lateral-effect and quadrant detectors¹⁶⁻¹⁹ can make precision measurements of angle and distance by sensing the lateral displacement of a beam of light on the photodiode. Resolution of 1 micron and better have been achieved. This translates to angular resolutions of the order of 0.001 degree. Lateral-effect detectors are commercially available at reasonable costs. Complere, Inc.²⁰⁻²¹ is currently under contract to NASA Ames Research Center to develop an angle of attack sensor using lateral-effects detectors.

The principle of operation is based on refraction of a light beam. Consider the diagram shown in figure 5a. An incident beam that is normal to the glass will pass through unaffected. When the glass surface is inclined to the beam path, the beam will be refracted and the emergent beam will be displaced. The displacement will be proportional to the angle between the surface and the incident beam. Thus, for a given thickness and refractive index, the beam angularity can be determined by measuring the displacement of the emergent beam. This measurement was done with a position sensing lateral-effect photo detector.

The Complere sensor system is shown in figure 5b. It consists of a laser mounted outside the test section and a lateral-effect detector assembly mounted in the model. The assembly consists of a filter, lens, glass plate, and photo detector. The laser beam is expanded and collimated to a large diameter so that the beams can more readily hit the detector. The detector assembly uses a mask or spatial filter and a lens to focus the beam onto the photodiode. The mask insures that light rays are incident at a fixed location relative to the detector, provided the aperture remains within the laser beam as the model angle is changed and/or fluctuates due to tunnel vibrations.

Initial wind tunnel tests of this system were done in the NASA Ames Research Center several years ago. Accuracy of 0.02 degree was achieved. It

is believed that the desired goal of 0.01 degree can be obtained by modifications to the receiving optics. The problem of signal drop-out due to tunnel fog were overcome by simple control of the detector light level gain. Even when the beam is blocked, the device immediately "locks on" once the beam is unblocked and the angle of attack is required.

During the past few years, development of this device continued. Newer, larger and more linear photodiodes are now available. Laboratory tests have shown that accuracies of 0.01 degree and better were achieved. Since the Ames Unitary Plan Wind Tunnel's sting can translate the model by about 6 inches as the angle of attack goes through its range to 15 degrees, a tracking system was developed. It consists of an accurate translation table to move the laser to follow the model. Preparations for installation in a model are being done. Calibration of the device will be done and operational problems will be studied. However, an actual wind tunnel test will not be done at this time. Wind tunnel time is not available. There is still the problem of making a window on the model to protect the detector assembly before a wind tunnel test. A model needs to be chosen such that the window geometry is simple, i.e. a flat or cylindrical surface, otherwise the manufacture of the window will be difficult.

The advantages of this system are (1) it operates in real-time, (2) there is no signal "drop-out" due to tunnel fog or obstructions, and (3) laboratory tunnels indicate that it has the required precision; however, a wind tunnel test must be conducted to confirm this.

Possible problems would be (1) need of a window that matches the geometry of the model, (2) operational environmental problems in the plenum of the 11 x 11 Foot Transonic Wind Tunnel, (3) any movement of the tracker system. Since a laser is required, laser safety problems must be addressed.

Saab Eloptopos

The Netherlands National Aerospace Laboratory purchased a Saab Eloptopos²² system for angle of attack measurements in the HST Transonic Wind Tunnel. The system consists of two infrared LED mounted fore and aft of the fuselage of the model, and two linear array CCD cameras mounted to the

test section side walls, see figure 6. The CCD camera has a 2048 pixel array with a 60 degree viewing angle to track the two pinpoint light sources from the LED's. A special algorithm was developed to increase the angular resolution of the camera to 0.001 degree. Germanium lenses were required because of the infrared wavelength of the LED. A narrow bandpass filter was used to reduce interference from ambient light. A calibration procedure was devised to account for model size (i.e. the length between the LED's) and for varying sting lengths (i.e. model location in the test section). The calibration was done at no flow conditions with the cameras fixed at given positions. An accurate electronic level was used to give the zero angle of attack to 0.001 degree. A Sundstrand Q-Flex servo-accelerometer mounted on the model was used to calibrate the Eloptopos over the angle of attack range. At typical viewing distances of one meter and a 700mm separation of the light sources, the angle of attack resolution was 0.0026 degree, about four times more than the goal of 0.01 degree. Lateral movement of the model will influence the angle of attack. For example, a change in viewing distance of 1 mm at 5 degrees will cause an error of 0.005 degree. Thus for optimum accuracy, the model should be at zero yaw and roll angles.

The Eloptopos system is now used routinely in the NRL tunnel. The data have shown a marked improvement in repeatability and better conformance between model upside-up and upside-down drag polars.

The advantage of this system is that it demonstrated the required accuracy in a wind tunnel. The cost of the system may be of the order of a hundred thousand dollars.

RAE Yaw Meter

The Royal Aircraft Establishment at Farnborough built a new laser yaw meter²³ for the RAE 5 meter pressurized wind tunnel. It was designed to continuously measure yaw angle to an accuracy of 0.1 degree over the entire angle of attack range. The laser yaw meter is based on a rotating fan of laser light shining on photodetectors on the model. The system consists of a 15 mw HeNe laser with optics to generate a fan or sheet of laser light, three collinear photodetectors, and an encoder for angular determination of the

photodetectors. The yaw angle is found by measuring the angular locations of the photodetectors relative to the light source. From the geometry, and knowing the three angles, θ_1 , θ_2 , θ_3 , and the two distances, L_1 and L_2 between the photodetectors, the yaw angle can be calculated, see figure 7. Although the RAE system was designed for a precision of 0.1 degree, this could be upgraded by using a thinner light sheet and a smaller pinhole in front of the photodetectors.

Selspot Camera System

The Selspot camera system²⁴⁻²⁵ is a commercial electro-optical tracking system sold by Selspot System Ltd. It has been used by J. George of General Motors for robotic guidance and by P. Laurich of the National Research Council of Canada for position monitoring of ship model in simulated sea states. The camera has a position sensitive device, i.e. lateral-effect detector as the sensing element. It can be used with or without a lens depending on the field of view. The Selspot hardware consists of a computer and a control system to measure the position of the LED targets.

A typical system consists of two cameras and two LED targets, figure 8. The camera would be spaced some distance apart to view the targets from different angles. Since the LED operate in the infrared wavelengths, infrared band-pass filters are used to reduce the background light and to ensure the LED targets are the only objects seen by the cameras. By pulsing the LEDs at different times, each LED can be correlated with its location. With two cameras, the three-dimensional coordinates can be derived with stereo-photogrammetry. A camera calibration is required initially to locate the LED targets in some coordinate frame system. Coordinate transformations have been derived; for example a coordinate based on the wind tunnel. The Selspot system can: 1. receive and digitize the position sensor analog position data, 2. individually strobe the LEDs and locate them in real-time, and 3. adjust the LED intensity for best contrast to the background lights.

In the robotic application, the Selspot tracked in a 1 meter cube volume to an accuracy of 1.5mm. It was found that the main source of error was reflections of the LED targets. Remember that this camera cannot distinguish between the

target or its reflections. Since the LED operate in the infrared, they cannot be seen and care must be taken to eliminate reflections. Calibration must be done precisely since any errors will be reflected in the data. Verification of the calibration must be done periodically.

In the model ship application, the Selspot cameras operate at a range of 7 meters. Comparisons to inclinometer tests showed pitch and roll angles were measured to within 0.15 degree.

Boeing BART

The Boeing BART is being developed by Boeing for angle of attack measurements. Preliminary tests in the Boeing Transonic Wind Tunnel showed that it will operate in a large wind tunnel. Preliminary tests showed that the accuracy is not as good as the Boeing Laser Angle Meter and further work is needed to improve its accuracy.

The BART device is based on the principle of a laser range finder.* Since Boeing considers the device proprietary, there are no references and information is sketchy. From conversations, the device uses a HeNe laser with a General Scanning scanner to track two or more retro-reflectors. The laser beam goes through an acoustical-optical crystal and is modulated. A beam splitter splits the beam with one beam being used as a tracking beam. The scanner puts out a 9-inch square checker pattern to look for the retro-reflector targets. The system measures the phase angle between the two beams and photogrammetry methods are used to calculate angular and space coordinates of the two targets. The field of view is 20 degrees and the range is the order of 10 meters. It is an absolute measurement system as any blocking of the beam will not cause it to lose track of the angle. It takes about a half second to relocate the targets.

*A typical laser range finder^{26,27} based on synchronized scanners uses geometric triangulation to locate objects in space. Basic elements of such a system consist of a laser, a scanning mechanism to project the laser beam onto the object, and a position sensor with a collecting lens looking for the light spot from the laser beam. The location of the spot in 3-D space is determined by triangulation by knowing the projection direction of the laser beam (i.e. the scanner angular position) measuring the direction of the spot by the position sensor, and knowing the distance between axis of the scanner mirror and the principal point of the collecting lens for the position sensor.

Line Scanner

Conversations with Joe O'Hare at AEDC indicated the precise angle of attack is not an important requirement in the Von Karman Wind Tunnels. A more important problem is to measure distances between probes and the model. A 1000 line scanner comparator is used to measure distances from shadowgraph photographs. Angles can be derived, but this process is tedious and not real-time.

Holographic Optical Elements

This is a conceptual idea to use holography to make angle measurement, hopefully much simpler. It utilizes some special properties²⁸ of hologram such as diffraction. Holograms can be used as mirrors but it also acts like a zone plate. Thus, as it reflects a laser beam, multiple order diffraction beams are reflected with strong variations in intensity in the different orders. The diffraction angles are also precisely known. Consider the scheme to measure angles with holograms as shown in figure 9a. A long hologram, long enough to accommodate the translational movement of the model is attached to the model. A laser beam from a laser mounted outside the test section shines on the hologram and the beam and its various diffracted beams are reflected. A sensor sufficiently longer will detect the positions of the reflected beams. The hologram is designed to ensure that the primary and 1st order beams will hit the detector as the angle of attack goes through its range of 15 degrees. From geometry, figure 9b, a simple equation was derived for the angle of attack based on the measurement of the reflected 1st order and primary beams.

The angle of attack, α , is found from the equation

$$\sin(b - 2\alpha) \sin(2\alpha + 180 - a - b - e') = \frac{B'}{E'} \sin(a) \sin(e')$$

where the angles a , b are found by measuring the distance B at zero angle of attack. Note that the triangle is an isosceles triangle.

At any arbitrary angle of attack, B' , E' are measured and the angle of the 1st order diffraction, e' is known from the property of the hologram.

Recommendations

1. Boeing is building a Laser Angle Meter for the Ames 11 x 11 Foot Transonic Wind Tunnel. Delivery is expected around December 1992. Coordination with Boeing is required for the design, safety, documentation and training. Preparation for a wind tunnel demonstration is also required. There is some documentation from a similar system built for NASA Langley about 10 years ago. In order to facilitate the wind tunnel demonstration, and learn how to use the system, Ames personnel should work closely with Boeing between now and December. This will require one or two trips to Boeing. A major effort may be required to design and install a motion system to enable the Laser Angle Meter to track the motion of the model as it goes through the angle of attack range. Compleare has a translation motion system for the Lateral-Effect Angle Sensor which may be suitable for the Boeing System.
2. The Compleare Lateral-Effect Angle Sensor is being installed in the Ames 14 Foot Wind Tunnel for a wind-off demonstration. Assuming this wind-off demonstration is successful, an actual wind tunnel test in the Ames 11 x 11 Foot Transonic Wind Tunnel is next. Money, manpower, and wind tunnel time must be scheduled. Estimates of \$30 to \$50K and a week of tunnel time are required.
3. The McDonald Aircraft Polarized Light Sensor has the potential of meeting the accuracy requirement. It does not use a laser and is relatively inexpensive, under \$10,000. Further inquiries for a cooperative test or borrowing the sensor for a test in the Ames 11 x 11 Foot Wind Tunnel should be pursued.

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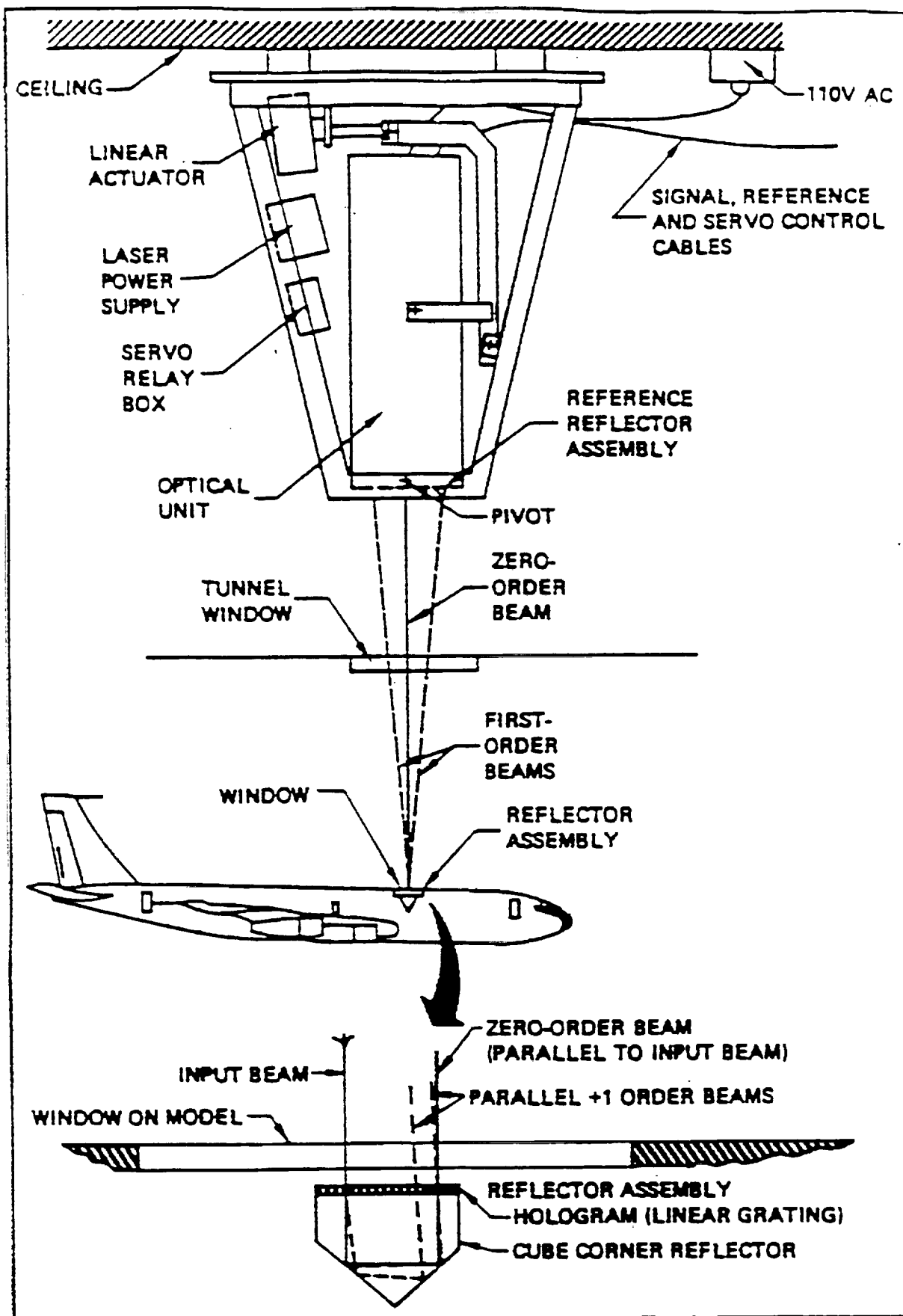


Figure 1. Boeing Laser Angle Meter. (after Pond and Hill)

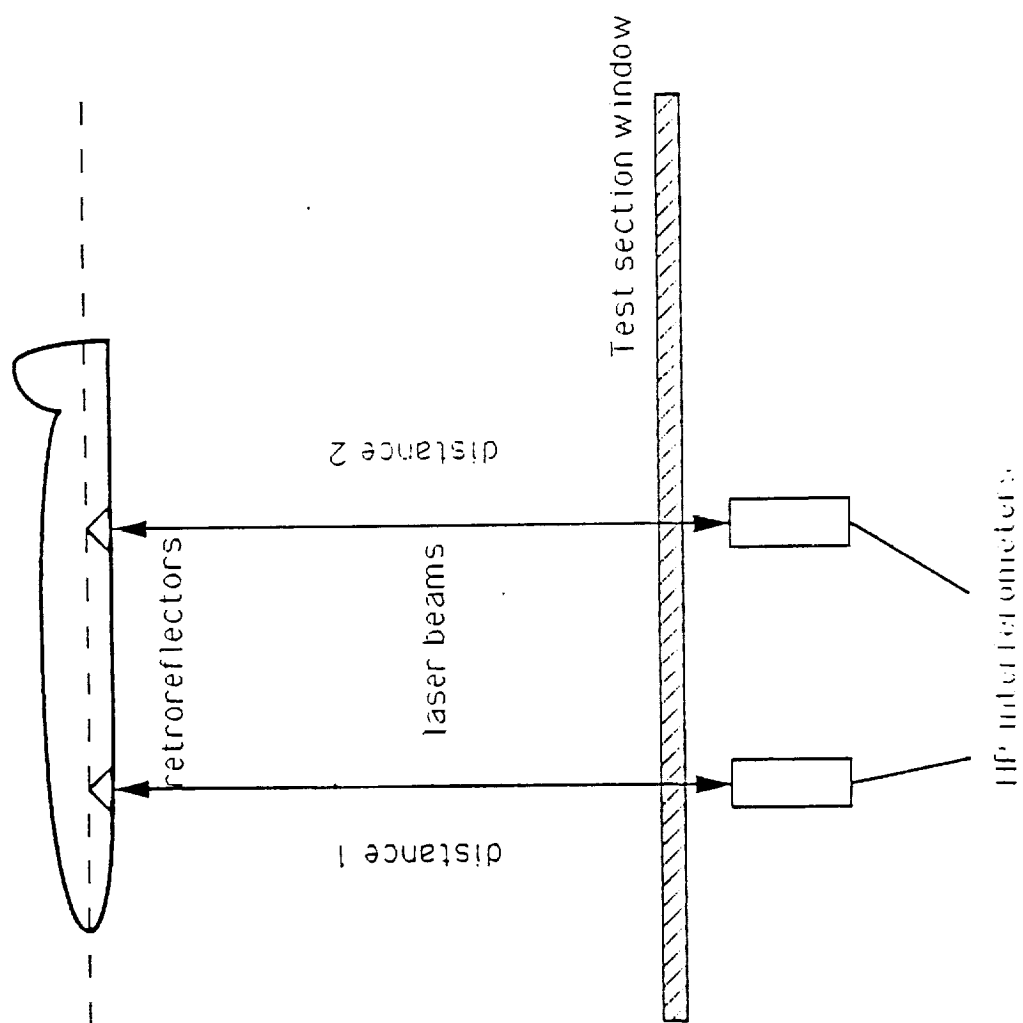


Figure 2. Angle Measurement Scheme using Hewlett-Packard Interferometers.

IMAPS (INFRARED MODEL ANGULAR POSITION SYSTEM)

ACCURACY = $\pm 0.03^\circ$

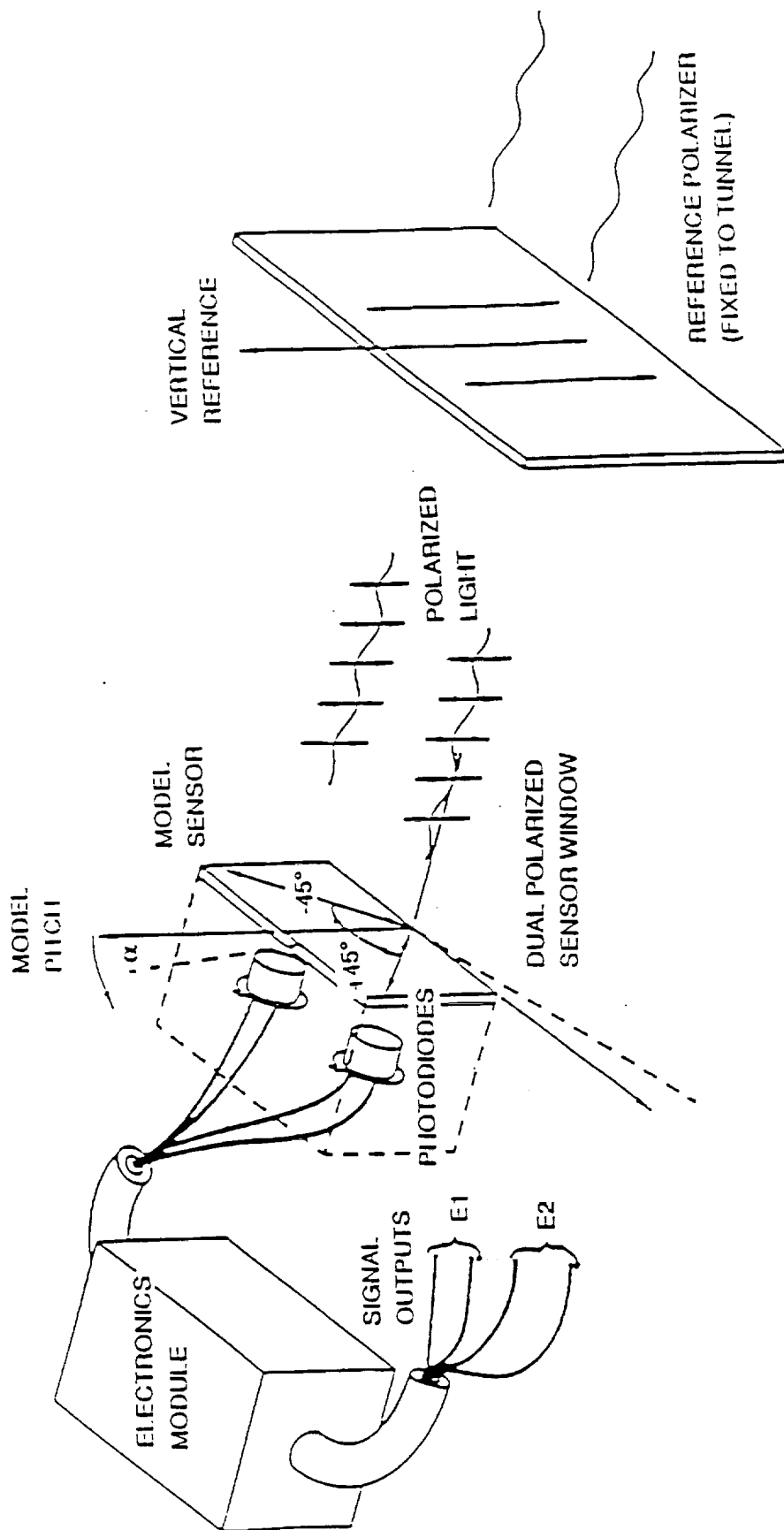


Figure 3. Polarized Light Angle Sensor. (after Crites)

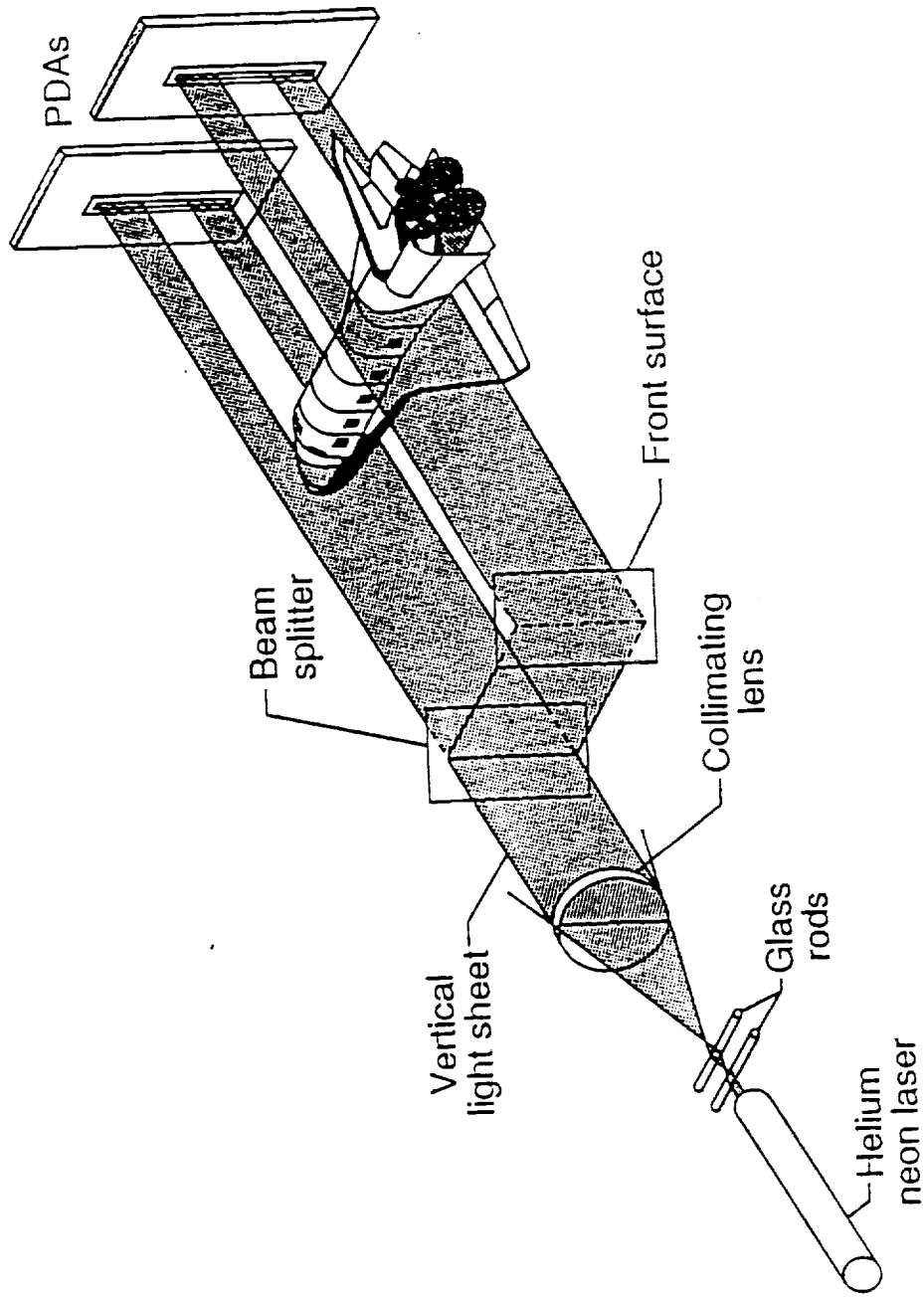
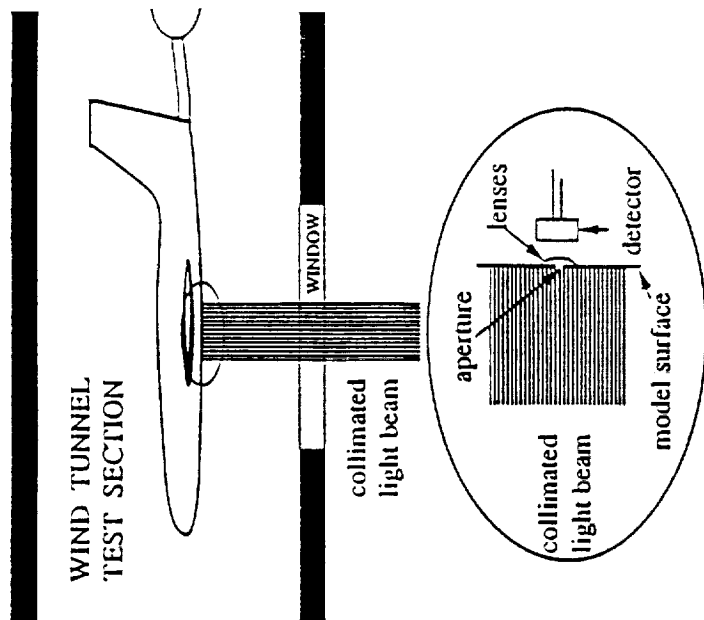
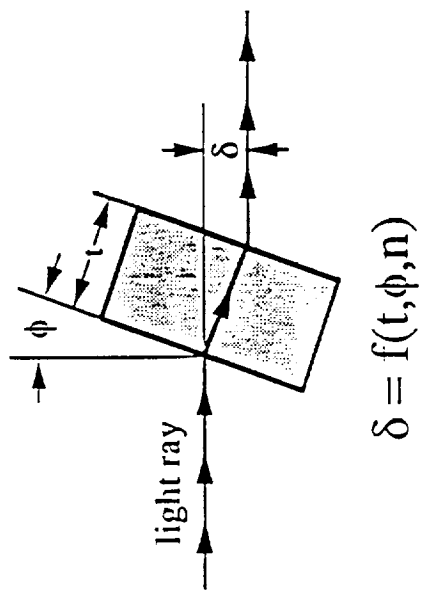


Figure 4. Linear Photodiode Array Displacement Measurement. (after Schott and Tcheng)



(b). Sketch of Sensor in Wind Tunnel.



(a). Beam Displacement Due to Refraction.

Figure 5. Complete Lateral-Effect Angle Sensor. (after McDevitt and Owen)

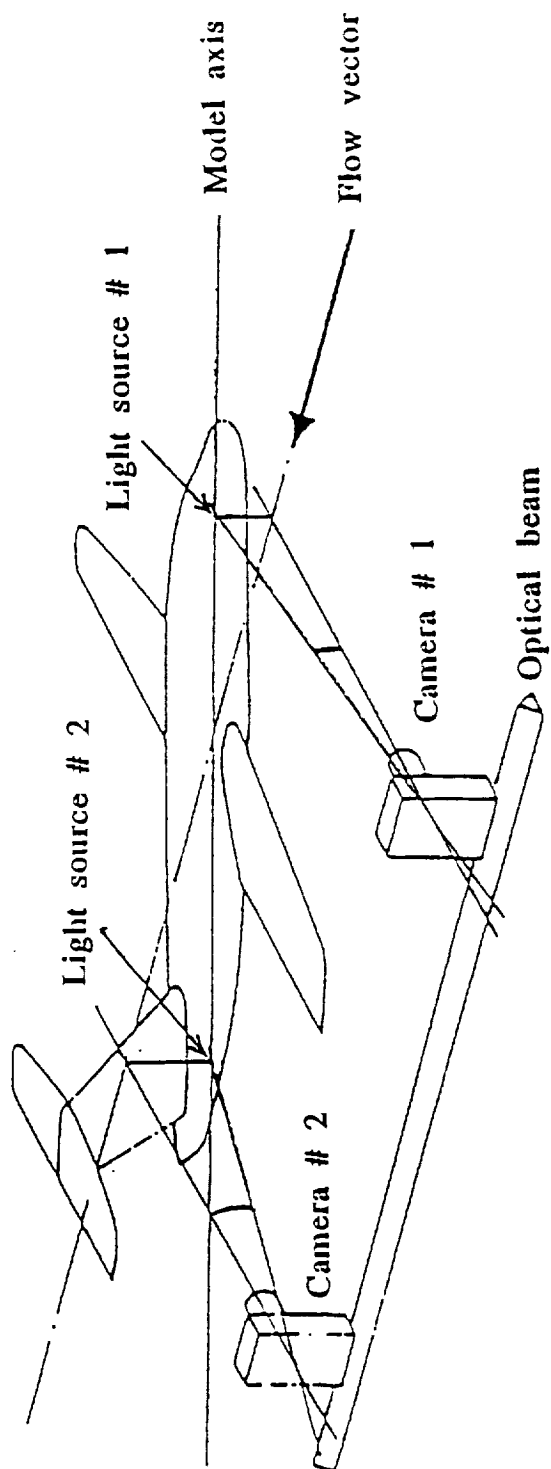


Figure 6. SAAB Eloptopos Angle Sensor. (after Fuijkschoot)

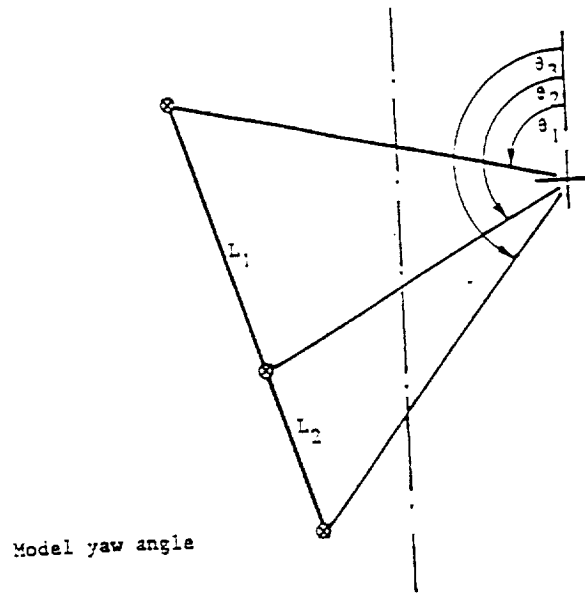
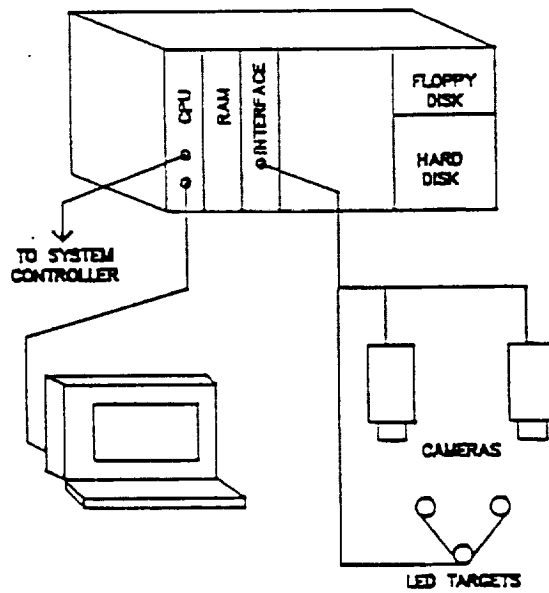
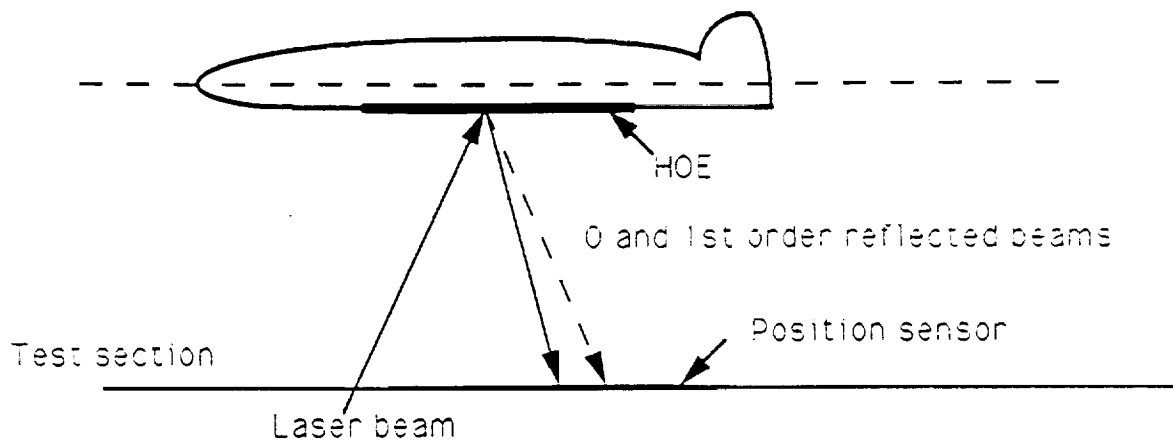


Figure 7. RAE Yaw Angle Meter. (after Jeffery, Tuck and Law)

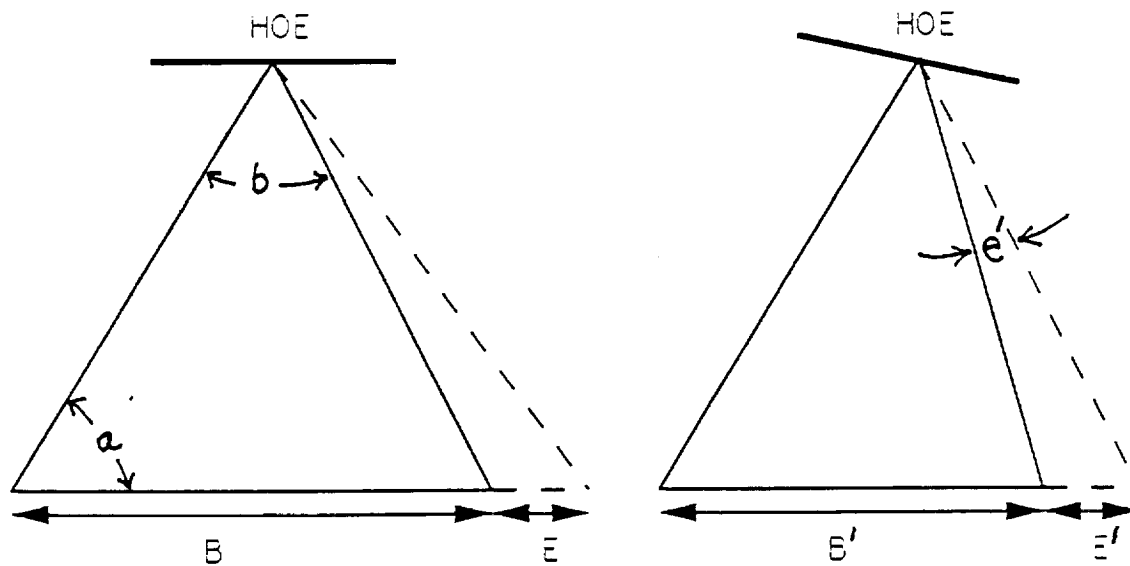


Selspot Hardware

Figure 8. Selspot Angle Measurement Scheme. (after George and Wolski)



(a) Wind tunnel setup



(b) Geometry at zero and any angle of attack

Figure 9. Holographic Optical Element Measurement Scheme.